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Universal droop controller for DC–DC converter interfaces onto a modular multi-tiered DC microgrid

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Abstract: Microgrids are usually based on single voltage levels, supporting a number of distributed generation sources and loads. This paper describes a multi-tier DC microgrid, with multiple voltage levels able to source and supply different power demands. A universal droop controller is developed for this multi-tier microgrid, able to connect uni- and bi-directional elements on to the grid. Simulations are used to demonstrate the functionality of the controller to allow autonomous load sharing based on decentralised control, with bi-directional power transfer between tiers to balance supply and demand at each level. Power can also be directly sent from one element of the microgrid to another, which is demonstrated through simulation, allowing for integration with future peer-to-peer energy trading systems.

1 Introduction

Microgrid systems have been developed in both grid-connected and islanded modes, to provide a simpler way to assimilate distributed generation into power grids, allow more reliable supply, and allow local generation and demand to match, reducing transmission losses [1]. Microgrids can be AC, DC, or a mixture of both, depending on the application of the system.

DC microgrids have become an attractive technology in modern electrical grid systems as a natural interface with renewable energy sources, electric loads, and energy storage systems; the number of power electronic converters interfacing the sources, microgrid, and load is reduced, when compared to the same AC microgrid systems [2–4]. Further improvement in reliability and efficiency of electrical grids can be achieved by utilising the DC distribution in microgrid systems.

At the heart of microgrids are the power electronic interfaces that link the sources to the microgrid, and several different control methods have been proposed for these interfaces [5–8], allowing for autonomous or centralised control of the microgrid, with different layers of control to achieve varying goals, relating to grid stability, voltage regulation, energy availability, and cost.

There is currently a lack of standardisation in DC microgrids, which is one of the main obstacles in their development when compared to AC systems [2], as without voltage standardisation, it is impossible to standardise appliances, devices, and equipment connected directly to DC grids. IEEE are attempting to address this through their working group on ‘Standard for DC Microgrids for Rural and Remote Electricity Access Applications’ [9].

The microgrids are often all based on a single voltage level, each source or load feeding into the grid at this tier. However, larger power systems are already formed from different tiers, with different voltage levels at each tier depending on the power transfer, which allow for reduced losses. For example, the UK national electrical grid voltage levels for the distribution and transmission range between 230 V AC RMS up to 400 kV. A DC multi-terminal microgrid, with individual nanogrids feeding from the central high-voltage network, has been proposed in [10] to support a zero-net carbon community, although it does not discuss how the power transfer can be controlled.

Academic and industrial interest continues to develop in direct peer-to-peer energy trading which entails direct coordination among distributed energy producers and consumers, or those who

can be described as a combination of the two so-called prosumers [11–12]. This cooperation between energy producers and consumers can maximise energy utilisation and reduce the need for storage, contributing in turn to reducing unit energy cost and carbon footprint [11]. Often the distributed sources and loads of interest are DC, such solar panels [12] and the provision of peer-to-peer electric vehicle charging [13]; therefore where such sources and loads are present, DC microgrids become a feasible option.

This paper will describe the proposed multi-tier DC microgrid concept, developing a universal control scheme to operate the system and demonstrating its operation through a series of simulations, including peer-to-peer energy transfer.

2 Multi-tier microgrid

The proposed DC multi-tiered microgrid is a combination of microgrids, with each level having a different power and line voltage rating. At the lowest level is the house, Fig. 1a, with a number of sources, storage and loads, each connected to the system with a power electronic converter, PE1. This is interfaced to the community level, Fig. 1b, through a second converter PE2, which connects a number of houses as well as medium-scale generation and storage elements. The community microgrid is then connected to the village-level grid through a third converter PE3. The village-level microgrid connects a number of different communities and larger scale storage and generation elements together, and then can be connected to a fourth converter PE4 to the grid, or to a further level of the microgrid.

The converters at each level can be modularised, so if a source has a greater supply power than the converter rating, they can then be connected in parallel. The advantages of this system are that converters on each level are identical assuming compatible voltage ratings, reducing complexity of design, and allowing houses to become electricity self-sufficient, or could choose only to be supplied by local power (e.g. community level). The drawbacks to the proposed system are the increased cost and potential reliability issues due to the number of power electronic converters within the system, but using modular converters can reduce any potential cost increase. This approach provides more precise control in each microgrid tier enabling ‘prosumers’ to exchange power directly with one another in a manner not currently possible in the grid. It can therefore facilitate a peer-to-peer energy trading system

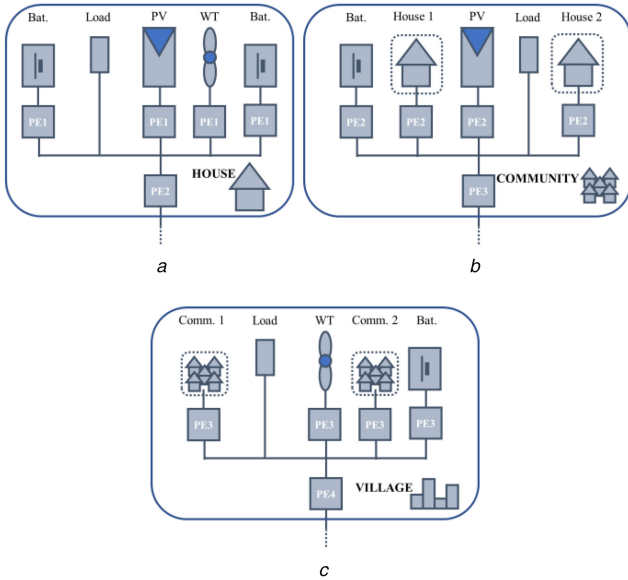


Fig. 1 Multi-tier microgrid levels: (a) House, (b) Community, and (c) Village

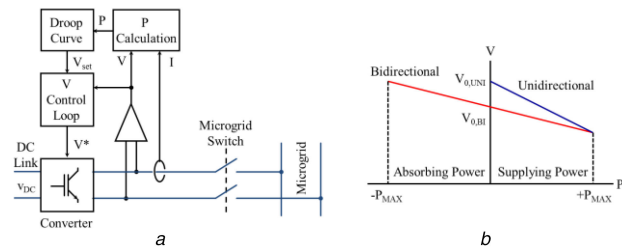


Fig. 2 DC-DC converter droop control details (a) Proposed droop control structure for converters. (b) Droop curves for uni- and bi-directional converters

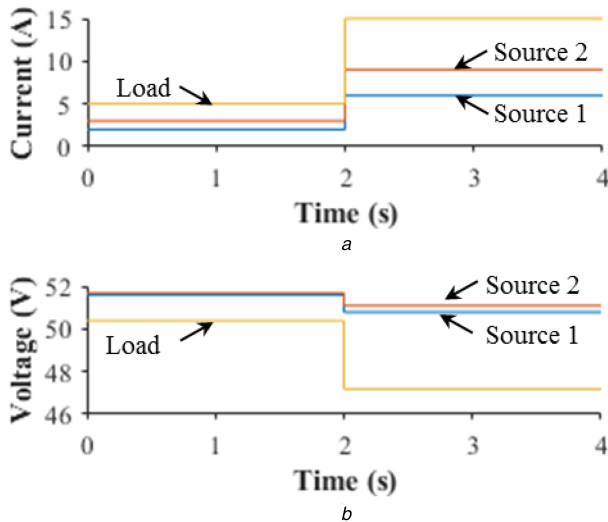


Fig. 3 Single-tier DC microgrid simulation demonstrating droop control characteristics

(a) Current and (b) Voltage measurements from simplified single-tier, two source DC microgrid simulation with a load current demand change at 2 s

between houses, communities, or villages within the microgrid, or to maximise income from any distributed generation and storage.

The multi-tier system proposed in this paper could operate in a number of different control scenarios: firstly, centralised, where each source is allocated a power output determined by a centralised processor dependent upon grid properties and setting the converter output parameters; secondly, supervisory, where primary control is decentralised with a secondary control system adjusting converter output parameters to regulate grid quantities; or thirdly,

decentralised, with each source using local measurements to set the converter output parameters. Decentralised autonomous operation provides greater security against failures of the main grid [14].

This work will develop and simulate the primary control system required for a decentralised multi-tier microgrid, which will be able to interact with secondary control or peer-to-peer-based systems.

3 Droop control design

Power-voltage droop control has been shown to operate well in DC microgrid simulations [15, 16], and is often used in its AC counterparts, to allow accurate load sharing between converter units using local measurements without the need for a centralised controller. The proposed control structure is shown in Fig. 2a. The output voltage and current are measured at the converter output, and the product is used to determine the power. This is then used in a droop curve, setting the output voltage as a function of the measured output power. The droop curves, as shown in Fig. 2b, for both uni- and bi-directional converters take the form of the following equation:

$$V = V_0 - mP \quad (1)$$

where V is the converter output voltage, V_0 is the voltage set-point, m is the droop coefficient, and P is the measured output power. For a unidirectional converter, for example a source element on the microgrid, V_0 is the maximum voltage on the grid. A bi-directional converter, such as a storage element or tier-linking converter (PE2 in Fig. 1), V_0 is the nominal grid voltage.

The droop coefficient is derived from the maximum power available from the converter P_{\max} and the maximum voltage drop ΔV such that

$$m = \Delta V / P_{\max} \quad (2)$$

The value of P_{\max} is able to change throughout the day, dependent on the resource available to the element; for example, as the solar insolation changes over a day on a photovoltaic (PV) system. This enables the source to contribute to the load dependent upon its generation capacity.

4 Simulation of single- and multi-tier DC microgrid

The following simulations are used to demonstrate the operating characteristics of the universal droop controller. As was discussed in Section 1, grid voltage levels for DC microgrids have not been standardised. For this work, we have assumed voltage levels of 50, 200, and 400 V, as these can match with existing power electronic devices, but the levels have no effect on the operation of the controller.

4.1 Demonstration of the DC droop controller

The first simulation is used to show the operation of the basic DC microgrid controller. The simulation comprises two DC sources connected to a 50 V nominal DC microgrid, each source with different droop coefficients, 1/250 V/W (Source 1) and 1/500 V/W (Source 2), with line resistance to load for each source being 0.1 Ω . At 2 s, load changes from 5 to 15 A. Results are shown in Fig. 3.

This figure shows that the sources are able to share out the load current as expected, dependent upon the droop curve gradient, with Source 2 supplying 50% more current than Source 1, and the voltage drooping as the output current increases.

4.2 Grid-connected single-tier DC microgrid

The second simulation represents a standard single-tier DC microgrid, operating over a 24-h period; the schematic diagram of the microgrid is shown in Fig. 4. The PV system, wind turbine, and battery scale the droop coefficient depending upon the insolation, wind speed, and battery state of charge, respectively. The insolation input data is taken from June data for Bristol, UK [17], and the

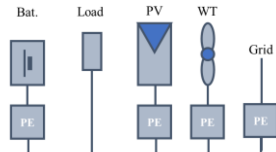


Fig. 4 Schematic of grid-connected single-tier DC microgrid used in simulation

Table 1 Single-tier grid-connected DC microgrid system parameters

Droop coefficient	Value, V/W	Line	Resistance, Ω
PV panel	1/250	line 1	0.1
wind turbine	1/250	line 2	0.2
battery	1/500	line 3	0.1
grid connection	1/2500	line 4	0.1

wind speed varies across the day with a mean of 5 m/s. The system droop coefficients and line resistance values are shown in Table 1. The load data is taken from [18], scaled to allow a maximum load of 500 W. The results for the current and voltage outputs can be seen in Fig. 5.

Fig. 5 shows that during the load peaks at ~6–7 am and 5–9 pm, the grid and battery augment the renewable sources, with positive current from both. During times of low load, 9 am–4 pm, the microgrid charges the battery and exports power to the grid, demonstrated by the negative current from the converter. As the day progresses and the insolation increases, the PV system provides a larger share of the current into the system, demonstrating the capability to adjust the converter power output dependent on its generation potential.

This simulation demonstrates how the control system can operate in a single-tier system with uni- and bi-directional converters, autonomously charging and discharging storage elements and able to import and export power from the grid in times of high demand.

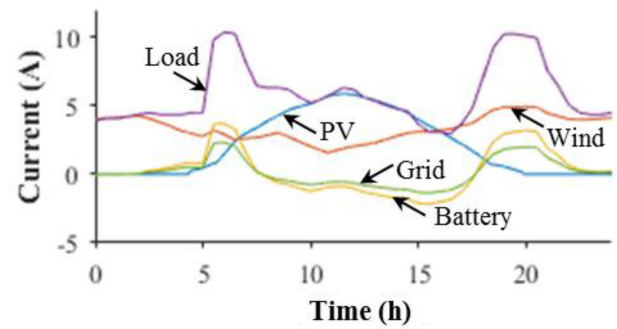
4.3 Basic multi-tier DC microgrid

A three-tier DC microgrid has been simulated to demonstrate the control in multi-tier operation; the system layout has been shown in Fig. 6. All converters are simulated as ideal voltage sources with constant droop coefficients. Within the simulation, converters PE1a, PE1b, PE2a, and PE3c represent sources, converter PE1c, PE2c, and PE3b represent storage elements, PE4a is the grid connecting converter, and PE2b and PE3a are the tier-linking converters, which are simulated as a pair of ideal converters, one to interface each tier.

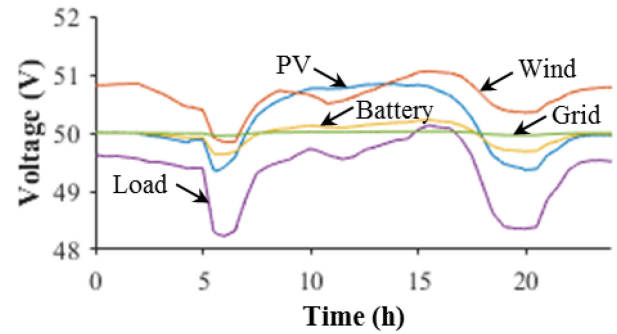
The tier-linking converters can deliver power as required for loads, using the voltage sag to determine the amount of power to transfer between the tiers. To achieve this in the simulation, the voltage set-point V_0 is varied in the upper tier converter to match the power generated or consumed by the lower tier converter. Fig. 7 shows the results for the simulation, with power transfer altering between the different tiers as load currents are changed in all tiers of the microgrid.

Fig. 7a shows that when the house load current is 15 A, both the house storage (PE1c) and community-tier (PE2b) supply power to the load. When the load current demand drops to 5 A after 2 s, the house microgrid tier then charges the storage and supplies power to the community tier, with associated increase in the grid voltage (Fig. 7b).

In the community tier, Fig. 7c, the impact of the imported current from the house tier can be seen with a drop in the supplied current from the other sources on the tier after 2 s. The community load current increases from 10 to 15 A after 3 s, which increases the output current from the community-connected source (PE2a), and requires power to be transferred from the village tier of the microgrid (PE3a). This is also reflected in the voltage drop, as shown in Fig. 7d at 3 s.



a



b

Fig. 5 Single-tier DC microgrid simulation over a 24 hour period in grid-connected mode

(a) Current and (b) Voltage simulation outputs for single-tier DC microgrid in grid-connected mode

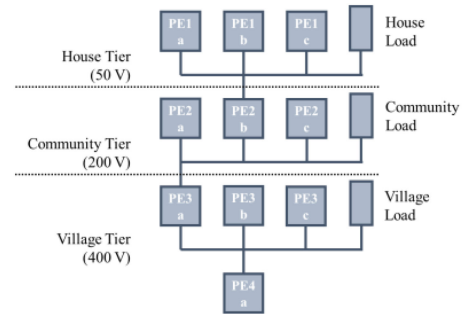


Fig. 6 Diagram of three-tier DC microgrid used in simulation with sources (PE1a, PE1b, PE2a, and PE3c), storage elements (PE1c, PE2c, and PE3b), tier-linking converters (PE2b and PE3a), and grid-connected converter (PE4a)

The village tier is affected by changes in both tiers below it, as can be seen by the current and voltage traces in Figs. 7e and f. The village load switches from 2 to 6 A after 4 s. The village source (PE3c) is able to supply this load by itself, and exports power to the grid (PE4a), whilst charging the storage element (PE3b) as well.

4.4 Power demand control in the multi-tier DC microgrid

The final simulation demonstrates how one element in the microgrid is able to transfer power to another, enabling the potential for peer-to-peer energy trading. Using the same layout as the previous simulation, as shown in Fig. 6, with the same loading patterns, after 3 s, the house tier-linking converter (PE2b) is commanded to import 500 W from the community storage (PE2c), at 4 s, it is then commanded to import/export no power, and then at 4.5 s, commanded to export 500 W to the community storage, as shown in Fig. 8. Fig. 9 shows the changes in the current and voltage in the house and community tier for this simulation.

Fig. 9a shows that at 3 s, when power is transferred from the community tier to the two sources (PE1a and PE1b), their current output decreases, with the storage (PE1c) absorbing additional

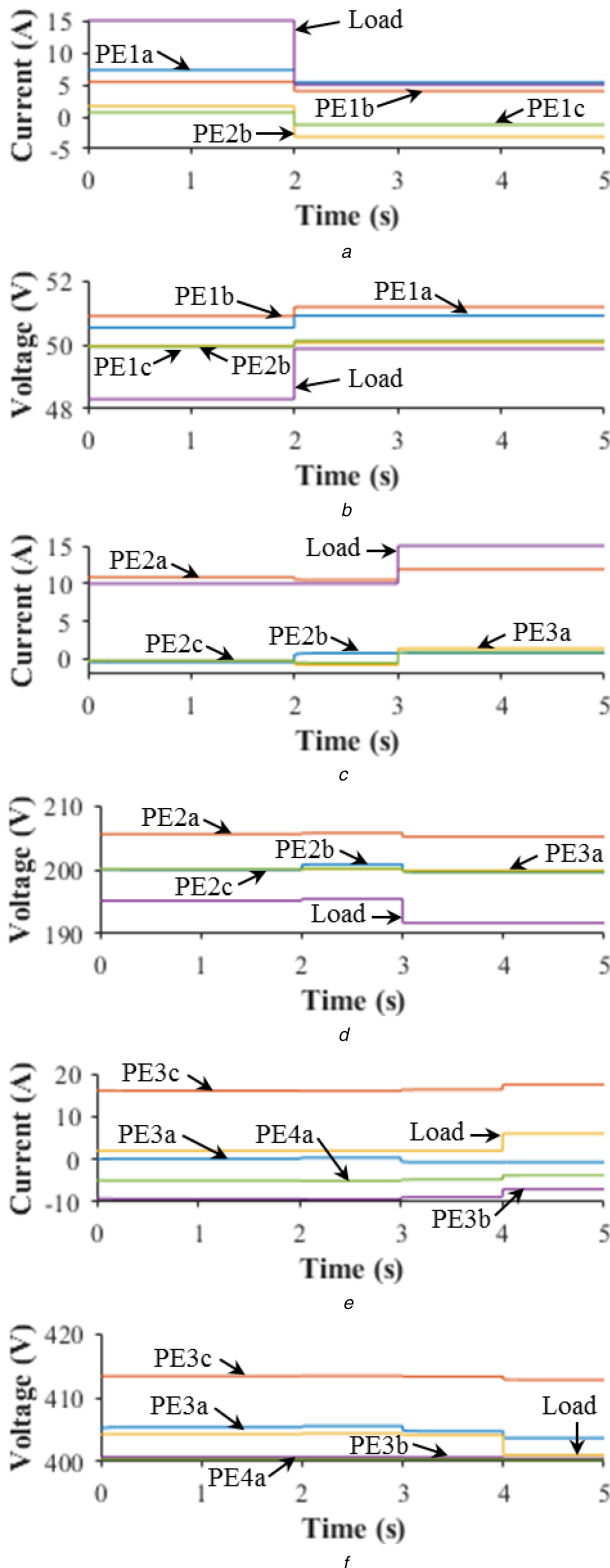


Fig. 7 Multi-tier microgrid simulation with varying generation and load
(a) Current and (b) Voltage in the house tier; (c) Current and (d) Voltage in the community tier; and (e) Current and (f) Voltage in the village tier

current. This is accompanied by an increase in the grid voltage, as shown in Fig. 9b. Then as the current imported from the community tier reduces to zero at 4 s, the house tier sources increase their output, with the storage absorbing less current. When the house tier exports power to the community tier, the two sources increase their power output further, with the storage required to supply power to the house tier as well.

On the community tier, as shown in Figs. 9c and d, as power is exported to the house tier (PE2b) from the community storage (PE2c) after 3 s, the community source (PE2a) generated additional

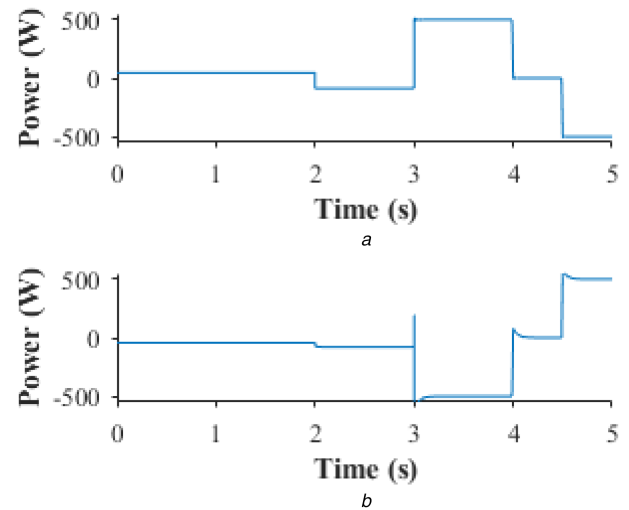


Fig. 8 Inter-tier power transfer demonstration in DC microgrid using universal controller

(a) Power imported/exported at the house tier-linking converter (PE2b) and (b) Power exported/imported into the community storage converter (PE2c)

power and extra current is drawn from the village tier (PE3a). As expected, this is reflected in a drop in voltage in the community tier grid, as shown in Fig. 9d. As the power transfer changes from export to import at 4.5 s, the current supplied from the source reduces and the community tier starts supplying power back to the village tier.

Therefore, this simulation has shown that the controller is able to operate within an energy trading environment, where power is transferred between different peers in the system.

5 Conclusions

This paper has discussed the multi-tier DC microgrid concept, developing a design for a universal controller for DC-DC converters to operate within it. The controller performance has been demonstrated through a series of simulations, in single- and multi-tier arrangements. The controller has shown that it is able to share the load between sources and across tiers without the need of an external controller, supplying power depending upon the generation capability. The power transfer between the different tiers of the microgrid was shown to change as the load altered; this was demonstrated to be able to be manipulated to allow energy transfer between peers across tiers which will enable integration with future peer-to-peer trading.

This paper presents the initial phase of work in this project. Further work will include the demonstration of the controller on custom-built and commercially available converters, integration within a hardware-in-the-loop test facility, and integration with peer-to-peer energy trading and demand-side management systems.

6 Acknowledgments

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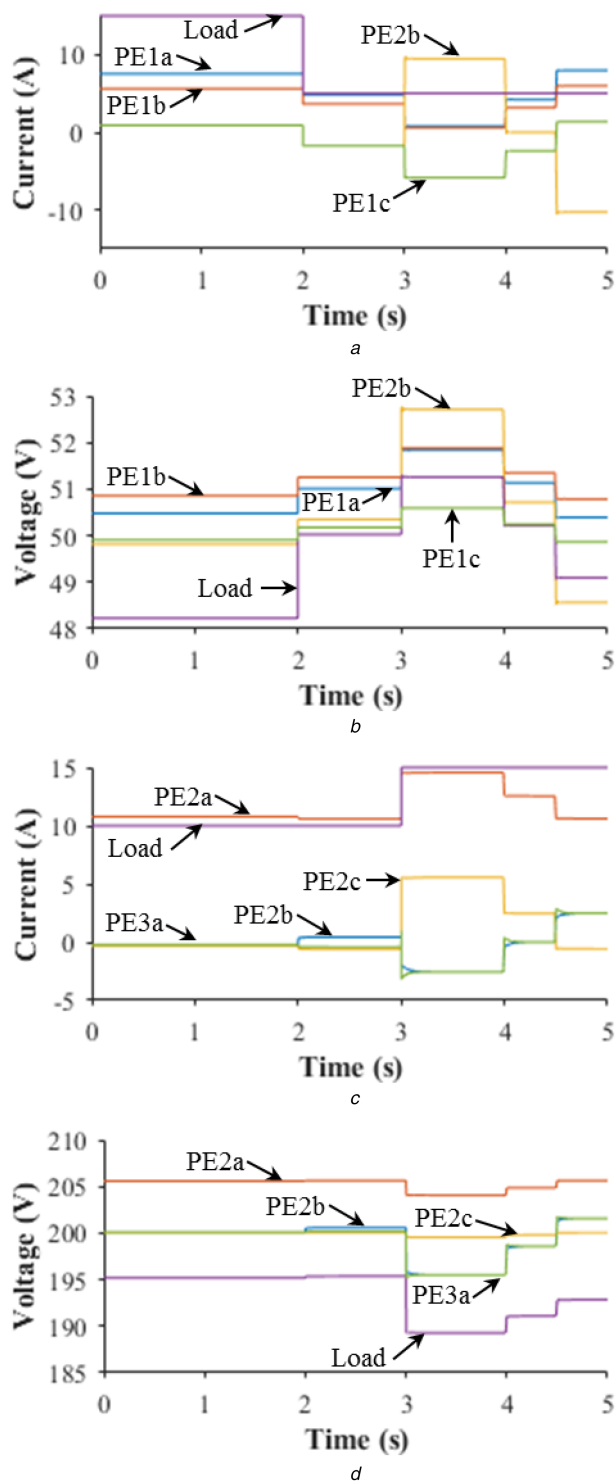


Fig. 9 Current and voltage waveforms during inter-tier power transfer demonstration in DC microgrid using universal controller
(a) House current, (b) House voltage, (c) Community current, and (d) Community voltage during power exchange between the house and community storage

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